


The Advanced Muon Facility at Fermilab: Physics and Relationship to the Muon Collider



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ENIGMA Collaboration

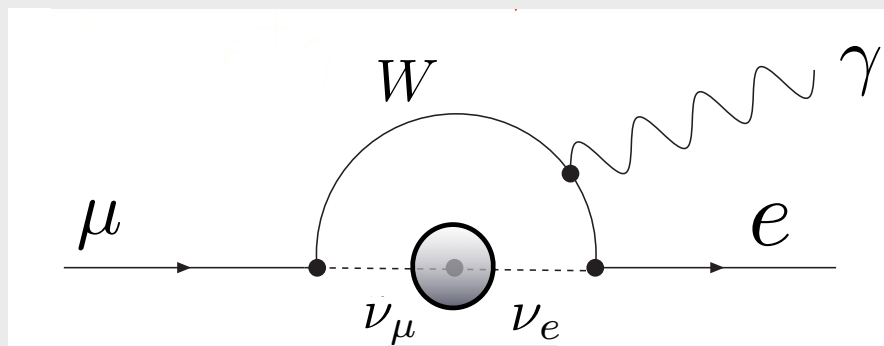
Muon Collider Physics and Detector Workshop
December 2022

Charged Lepton Flavor Violation

- Transitions among $\mu \leftrightarrow e \leftrightarrow \tau$ without neutrinos
 - cannot be weak interaction: non-SM process
- Directly linked to questions of flavor and generations
 - we observe mixing in quarks and neutral leptons: why not charged?
- Muon CLFV has been under study since the discovery of the muon; taus are also important

Neutrino Oscillations and Muon-Electron Conversion

- ν 's have mass! *individual lepton numbers are not conserved*
- Therefore Lepton Flavor Violation occurs in Charged Leptons as well

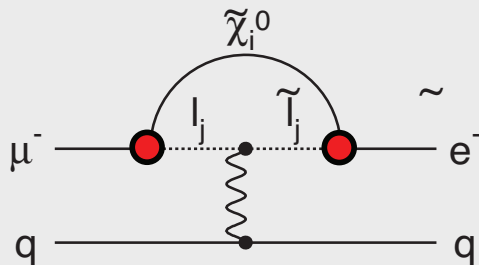


$$\text{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

Contributions to Muon CLFV

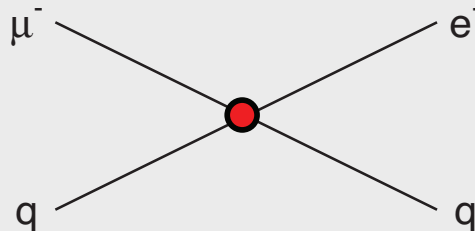
Supersymmetry

$$\text{rate} \sim 10^{-15}$$



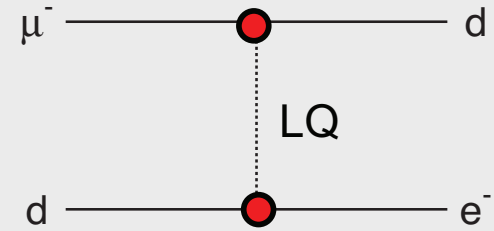
Compositeness

$$\Lambda_c \sim 3000 \text{ TeV}$$



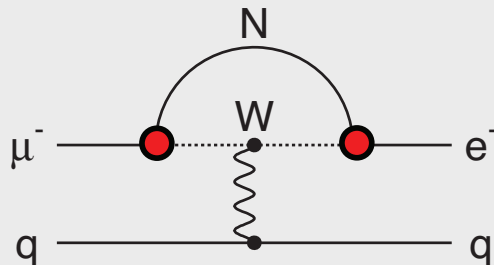
Leptoquark

$$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{e d})^{1/2} \text{ TeV}/c^2$$



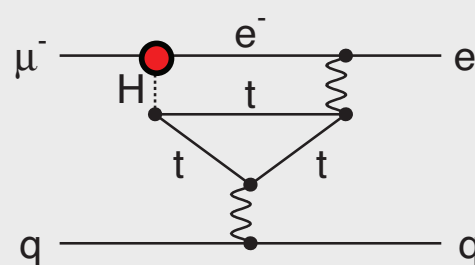
Heavy Neutrinos

$$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$$



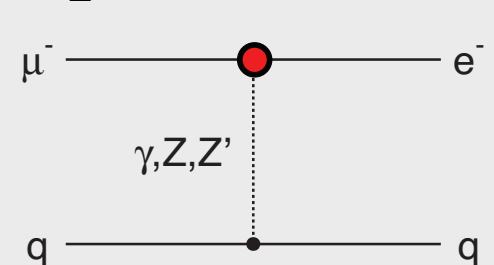
Second Higgs Doublet

$$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu \mu})$$



Heavy Z' Anomal. Z Coupling

$$M_{Z'} = 3000 \text{ TeV}/c^2$$



also see Flavour physics of leptons and dipole moments, [arXiv:0801.1826](https://arxiv.org/abs/0801.1826) ;
 Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:[10.1146/annurev.nucl.58.110707.171126](https://doi.org/10.1146/annurev.nucl.58.110707.171126) ;

CLFV Muon Processes

- $\mu \rightarrow e \gamma$

- oldest studied, most powerful limits, and the best experiment so far: MEG at PSI

- $\mu N \rightarrow e N$

- muon to electron conversion: muon converts in field of nucleus, leaving nucleus unchanged

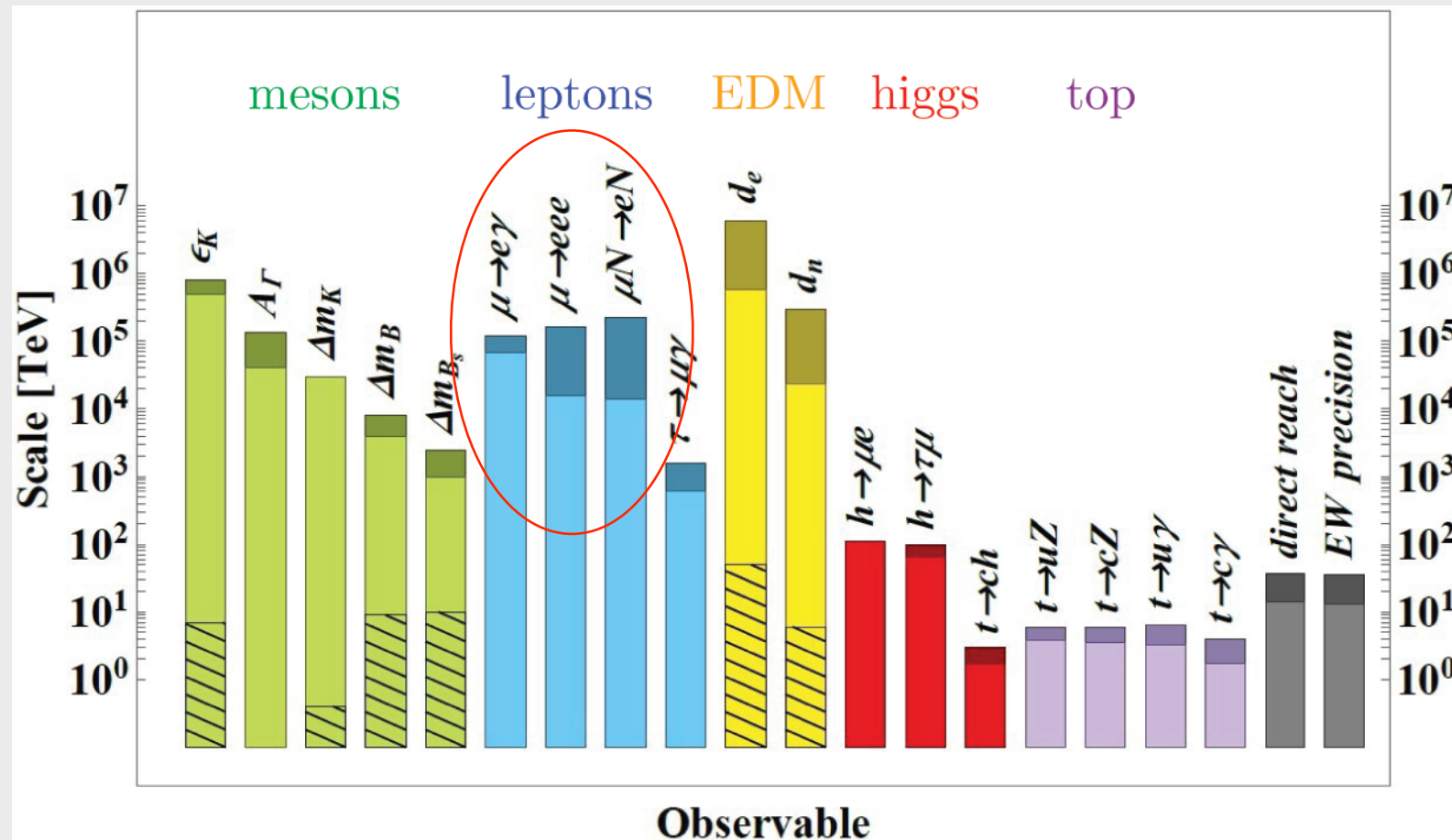
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A, Z) \rightarrow e^- + N(A, Z))}{\Gamma(\mu^- + N(A, Z) \rightarrow \text{all muon captures})}$$

- two experiments upcoming at FNAL and JPARC

- $\mu \rightarrow e e e$

- ambitious and unique, excellent partner to other two (at PSI)

Mass Scales of Muon CLFV Searches

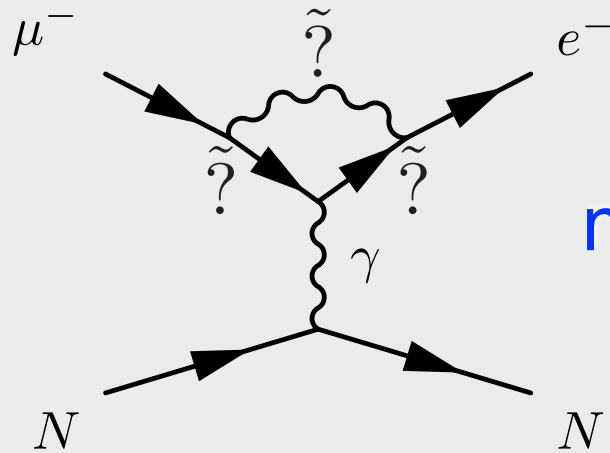


operator coefficients =1, from Physics Briefing Book, 1910.11775

Toy Lagrangian

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{1}{\Lambda^2} \bar{\mu}_L \gamma^\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L)$$

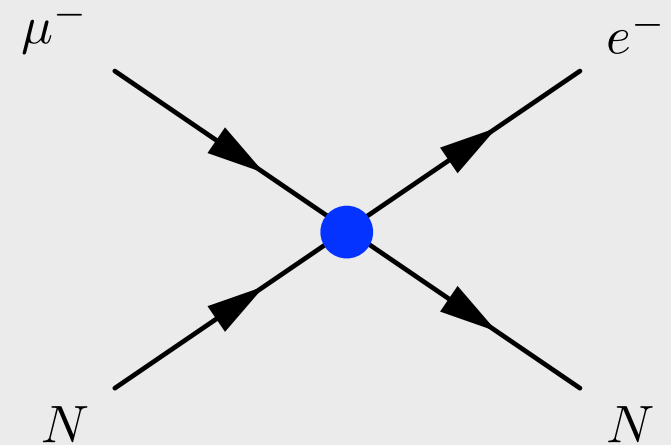
“Loops”



Supersymmetry and Heavy Neutrinos

mass scale Λ

“Contact Terms”



New Particles at High Mass Scale (leptoquarks, heavy Z,...)

Contributes to $\mu \rightarrow e \gamma$

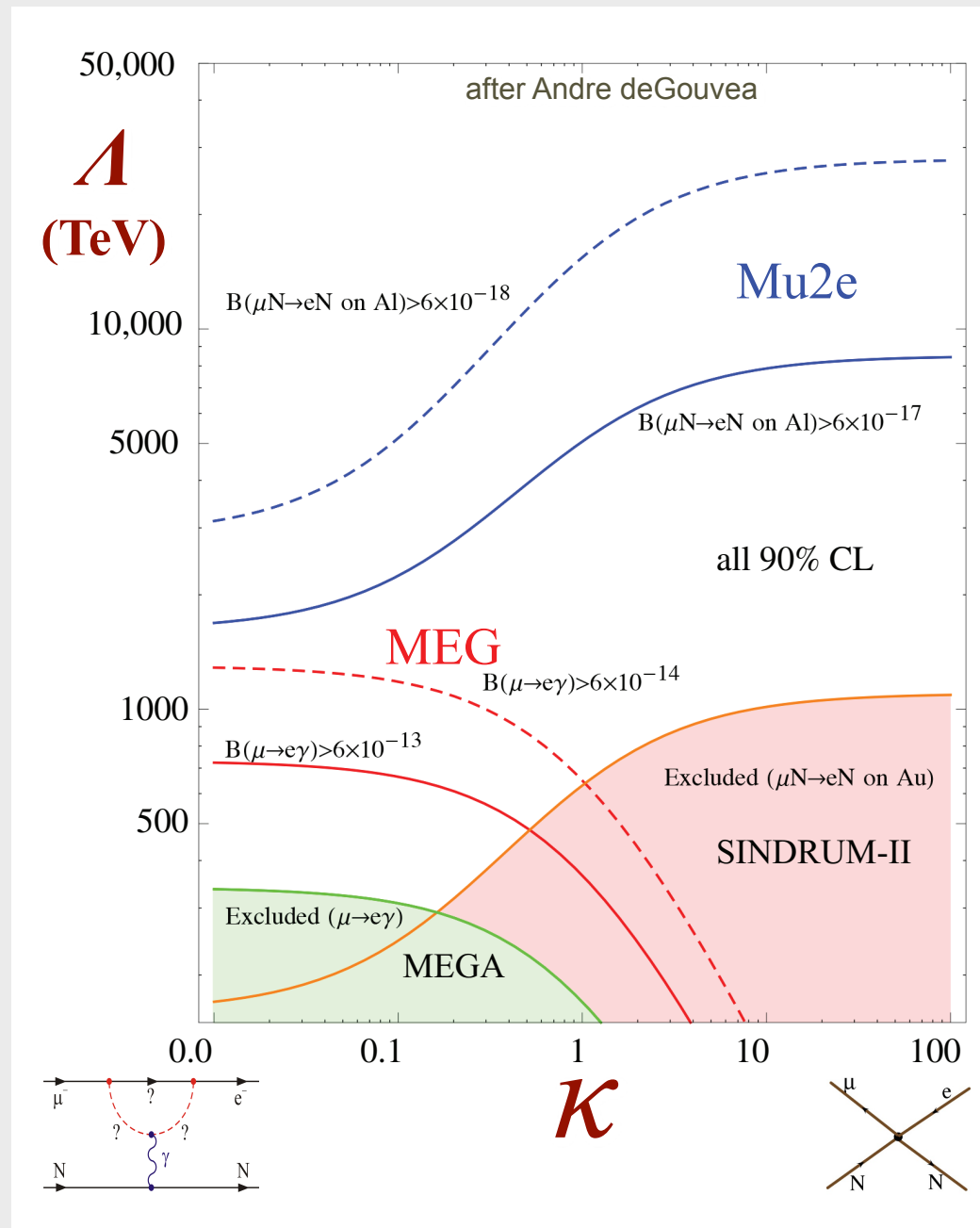
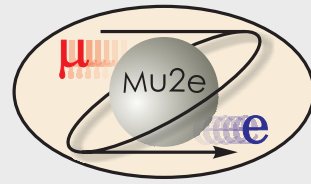
(just imagine the photon is real)

Does not produce $\mu \rightarrow e \gamma$

A. DeGouvêa and P. Vogel, [1303.4097v2](#) [hep-ph]

for EFT treatment see S. Davidson and B. Echenard, [2010.00317](#) [hep-ph]

“DeGouvea Plot: 2013”



de Gouvêa and
Vogel, 1303.4097

EFT: Beyond Λ and κ

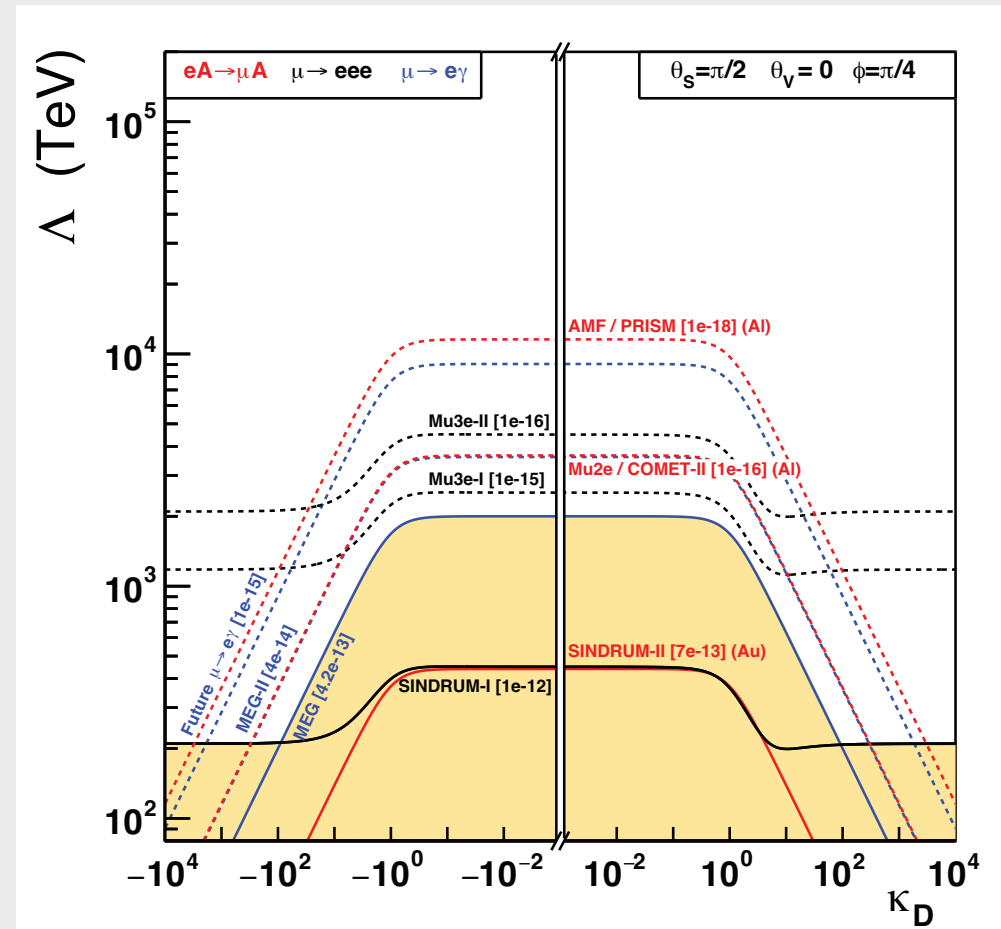
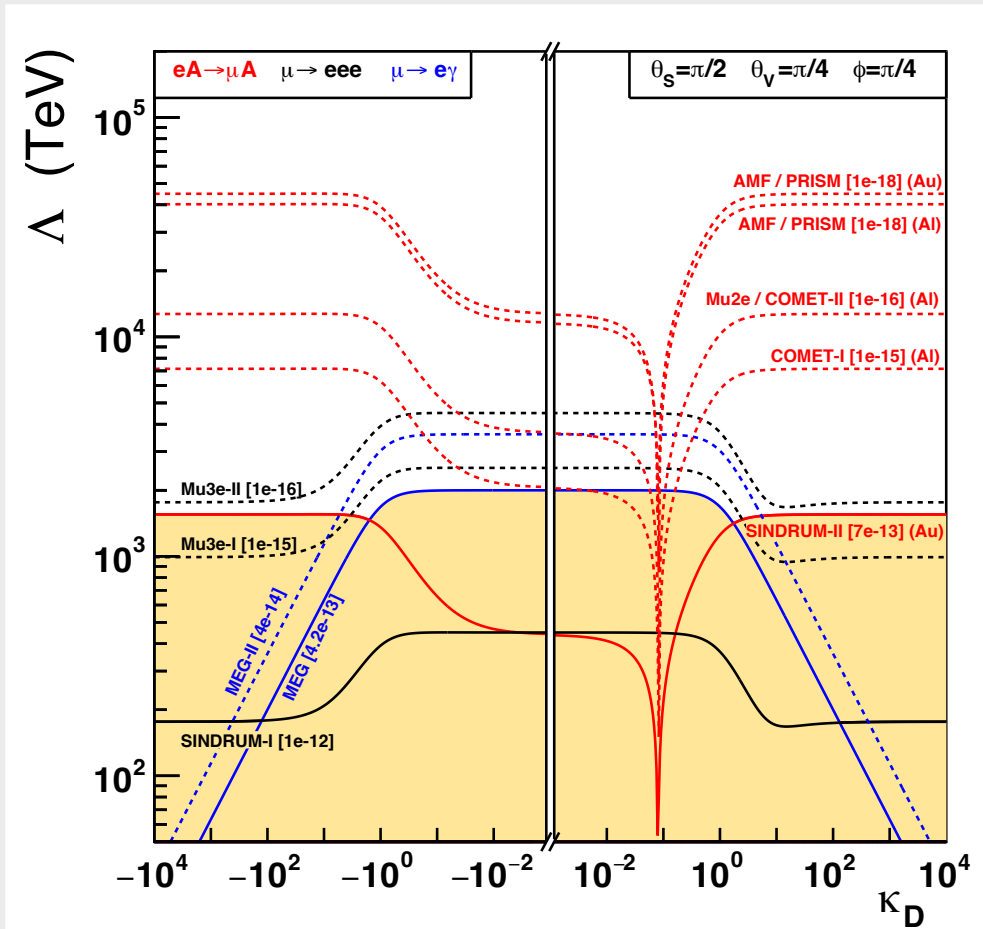
S. Davidson and B. Echenard, [2010.00317](#) [hep-ph]

- Write EFT Lagrangian:
 - Dipole ($\mu \rightarrow e\gamma$) +
Contact Scalar ($\mu \rightarrow 3e$)_L +
Contact Vector ($\mu \rightarrow 3e$)_R +
Contact $\mu N \rightarrow eN$ (light nuclei) +
Contact $\mu N \rightarrow eN$ (heavy nuclei)
- Parameterize coefficient space with spherical coordinates: *lets you express constraints on all three processes simultaneously*
- Will show you “slices” in the multi-dimensional space

Complementarity

S. Davidson and B. Echenard, 2010.00317 [hep-ph]

- All three channels have strengths; we need the combination



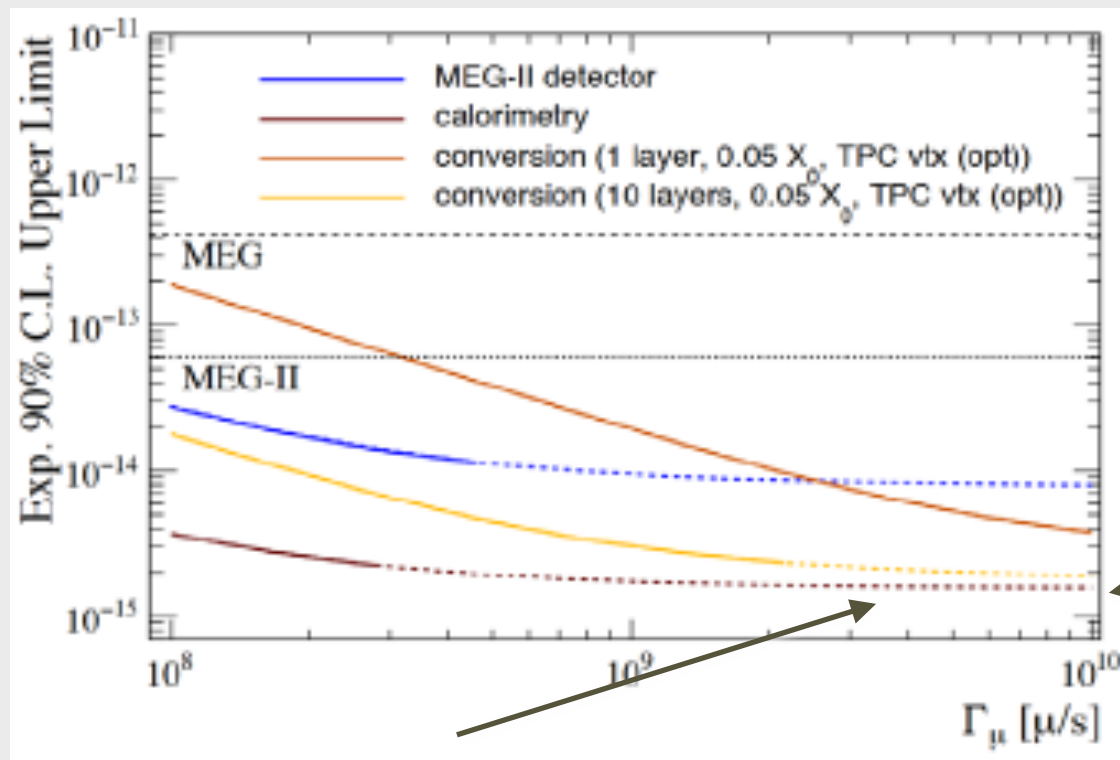
- $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ at $\mathcal{O}(10^{-15})$ are a next-gen target

Decay Experiments

- $\mu^+ \rightarrow e^+ \gamma$ and $\mu^+ \rightarrow e^+ e^+ e^-$
 - these bring low energy (~ 30 MeV) μ^+ to rest in material and observe the decay (surface muon)
 - in $\mu^+ \rightarrow e^+ \gamma$, accidentals scaling as I^2 are the limit; accidentals come from multiple muon decays and resolution limits
 - since accidentals drive the background, we want as continuous a beam as possible
 - in $\mu^+ \rightarrow e^+ e^+ e^-$, additional bkg from radiative muon decay, $\mu^+ \rightarrow e^+ e^+ e^- \nu_e \bar{\nu}_\mu$ with small E_ν

$\mu \rightarrow e\gamma$ Limits

- $\mu^+ \rightarrow e^+\gamma$ as in MEG, but convert the photon for improved resolution (have a vertex from tracks)
- lowers statistics by $\sim \times 100$ but improves background rejection



levels out at
 $10^{10} \mu/\text{sec}$,
about HiMB
PSI upgrade

Renga et al., 1811.12324[hep-ex]

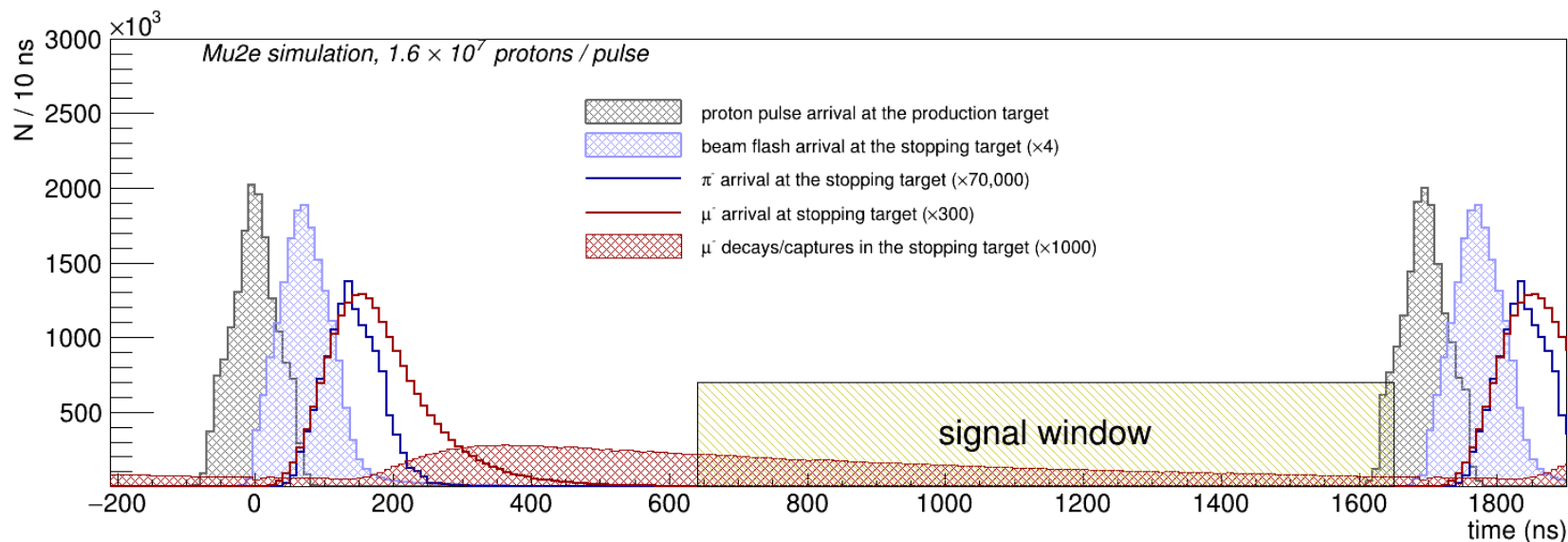
next-gen 10^{-15} goal for $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$

Capture Experiment

- $\mu^- N \rightarrow e^- N$
 - brings a muon near an atomic nucleus where it falls into a muonic 1s state: monoenergetic electron just below m_μ
 - for several generations of experiments, including Mu2e/COMET, the beam design was driven by radiative pion capture (RPC):
 - $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+ e^-$ at the signal energy
 - Mu2e/COMET use a *pulsed* beam and use the 26 ns pion lifetime vs $2.2 \mu\text{s}$ muon lifetime to “wait out” RPC

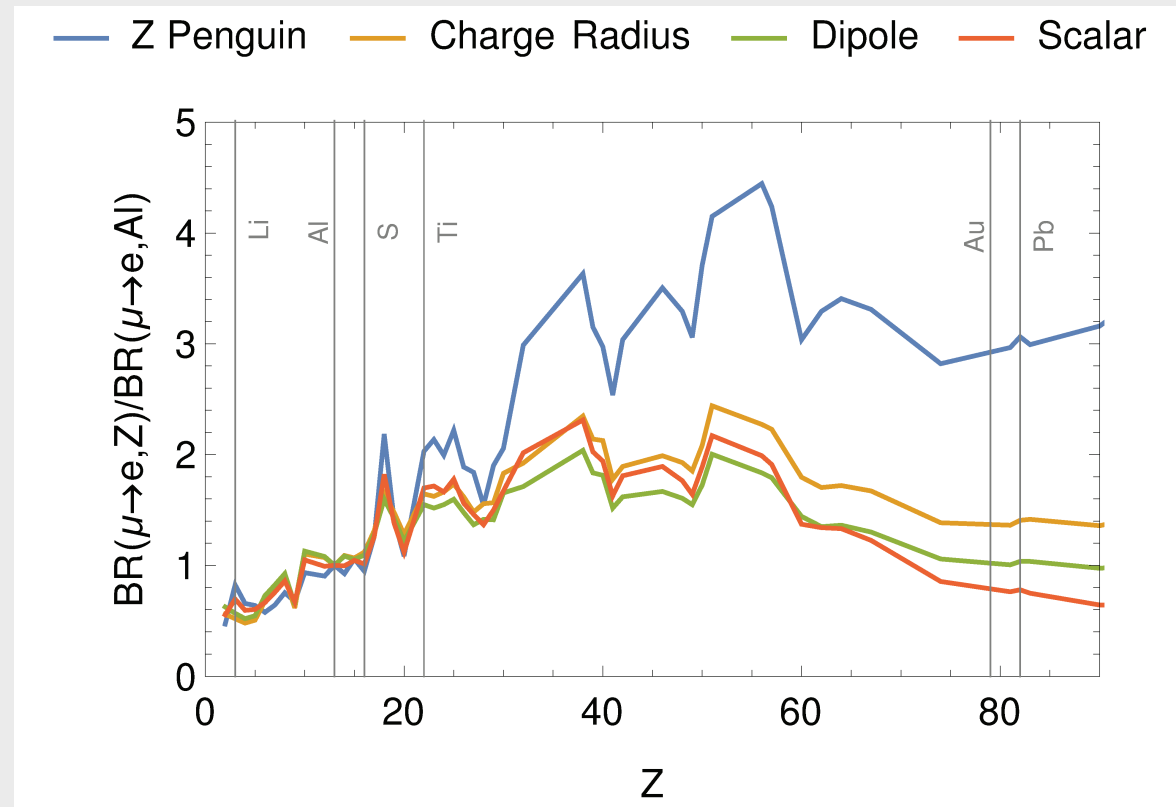
Mu2e/COMET timing scheme

- Complicated plot, but for both Mu2e/COMET
 - pulse at beginning
 - wait for pions to decay
 - open a signal window



Conversion at Higher Atomic Number

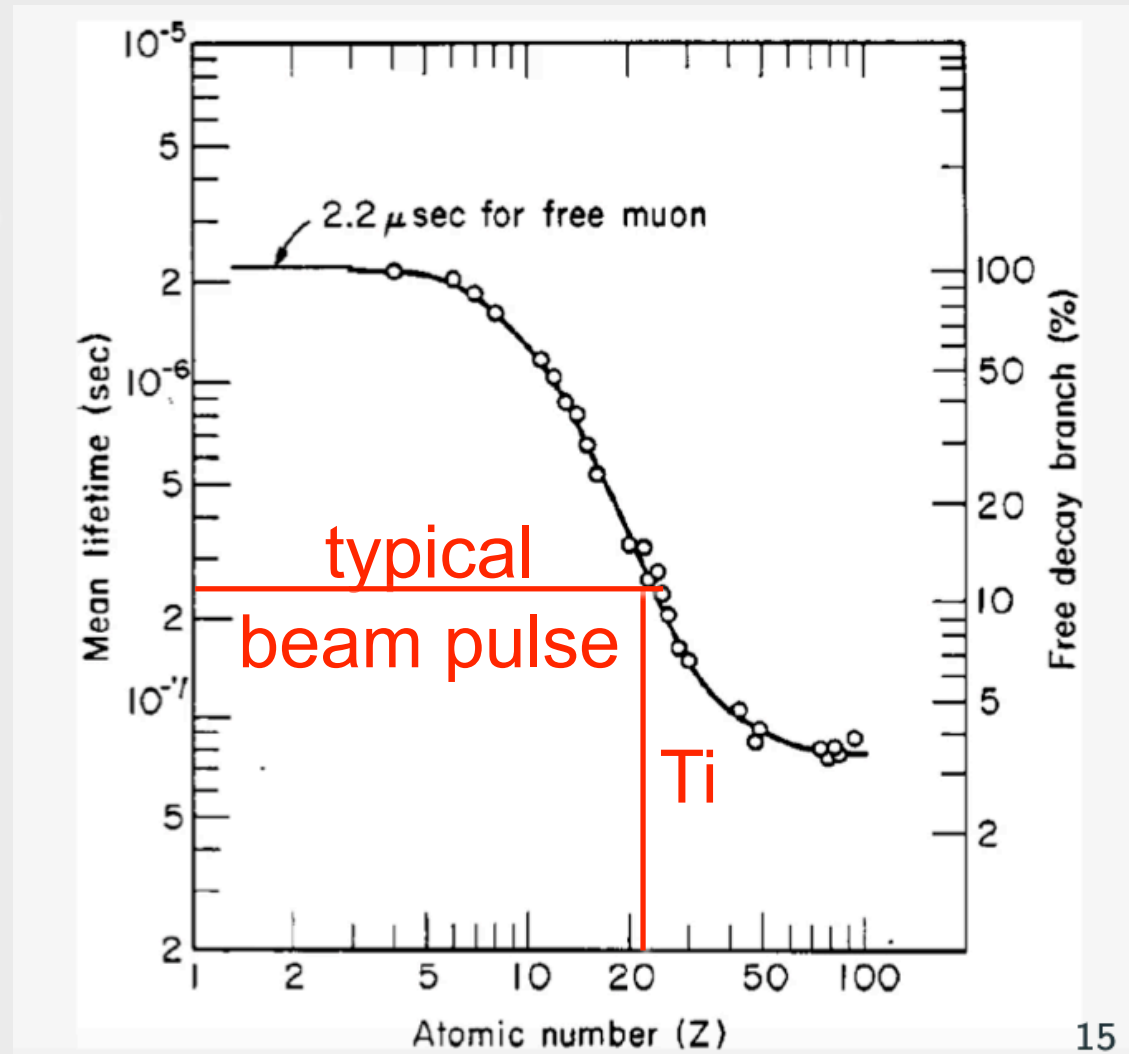
- Model Discrimination and Possibly Larger Signal at high Z
- if Mu2e sees a signal, this is the obvious next step
- if not, we should try for another $\times 10$ -100 better constraints



adapted from V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005**

Limitation of Mu2e Method

- A beam pulse is ~ 250 ns FWHM
- You can't do an experiment inside the debris from the beam pulse
- And therefore you can't go to high Z : Ti about limit



15

New Facility: AMF

hep-ex 2203.08278

- The “Advanced Muon Facility” would use PIP-II to enable
 - ***CLFV in all three muon modes: world-leading facility***
 - two new small rings for $\mu N \rightarrow e N$ at high Z and additional x100 in rate
 - with a possible DM experiment
 - x100-1000 more beam for $\mu \rightarrow e \gamma$ and $\mu \rightarrow 3e$ than are possible at PSI
 - Possible muonium-antimuonium and muon EDM

Conversion Physics

- Like Mu2e, target beam inside a solenoid, but at 100 kW - 1MW vs. Mu2e's 8 kW
 - Mu2e-II at 100 kW, but not high Z
- Rebunch PIP-II beam in a “compressor ring”
- bring to proton target
- Transfer to a fixed-field alternating (FFA) gradient ring
 - phase rotates to slow higher momentum muons, accelerate lower momentum muons
 - pion contamination greatly reduced while muons are circulating in ring (same notion of using π decay as Mu2e)
- Extract pure, cold muon beam to detector

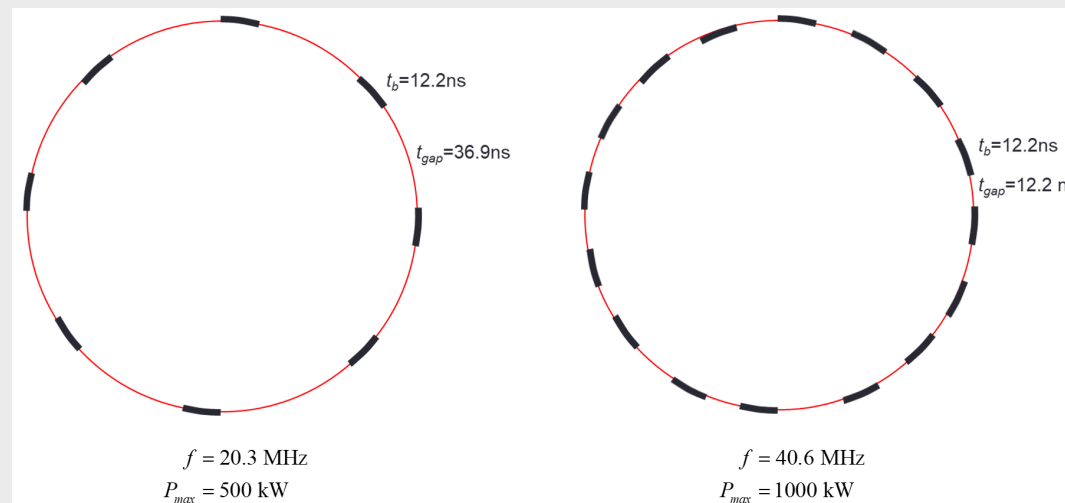
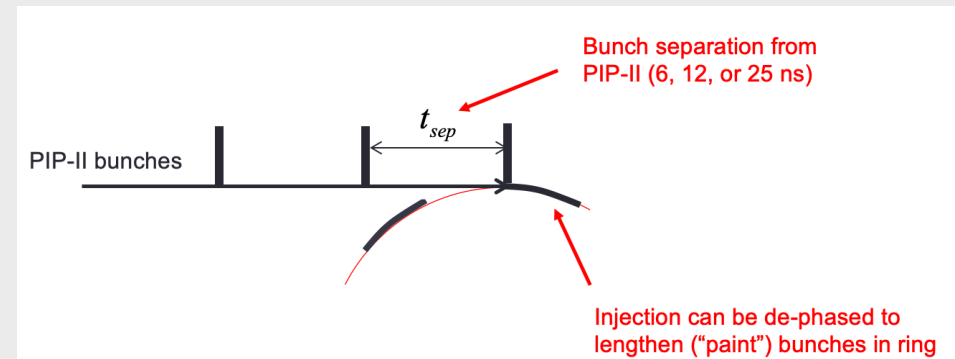
the FFA for conversion from Japan:

<https://indico.fnal.gov/event/46669/contributions/203147/attachments/138314/173082/>

PRISM_CLFV_10122020_Pasternak.pdf

Beam for Conversion

- Compressor Ring:
 - 500 kW achievable;
 - 12 ns kickers are the limit for 1 MW



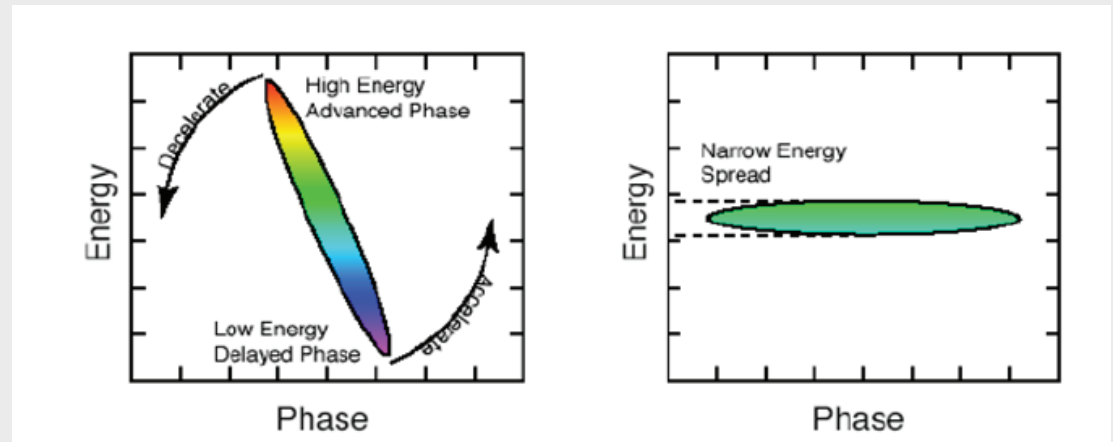
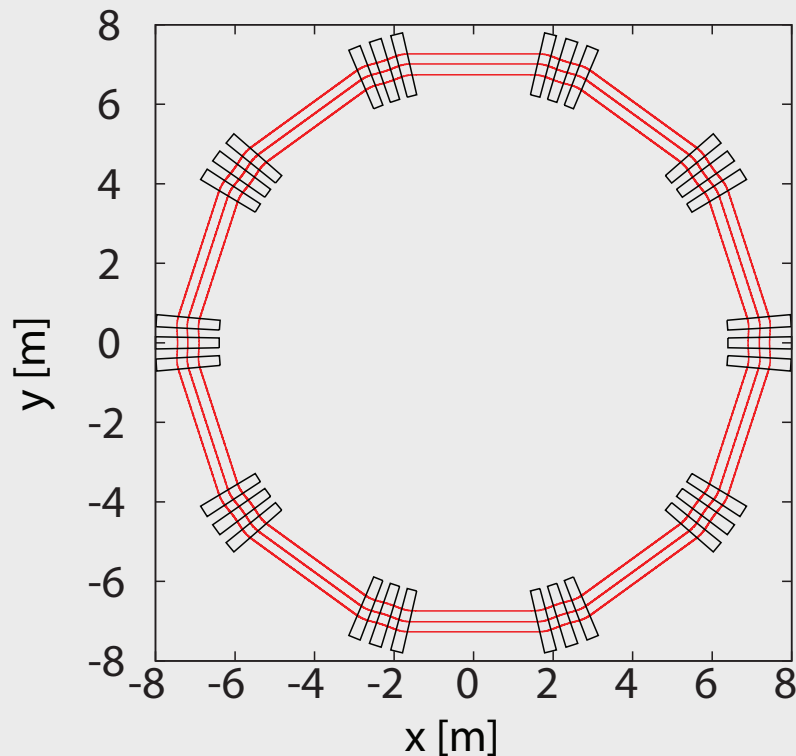
Description	Protons-Per-Pulse	Pulse Spacing (ns)	Repetition Rate (Hz)
AMF	7.8×10^{13}	24	100
Dark Matter	6.2×10^{14}	196	100

Production Solenoid

- Mu2e at 8 kW requires a complicated heat and radiation shield to keep superconductor from quenching; COMET proposes 56 kW
- Mu2e-II Conceptual designs exist for 100 kW
 - “moving mass” target and thicker shield
- AMF would provide world-class physics at high-Z; 100 kW is just the first step
- Various ideas for 1MW have been promoted
 - ν targets for DUNE get to 1MW...why so hard?
 - *not inside a superconductor*

FFA

- PRISM (Phase Rotated Intense Source of Muons)
(arXiv:1310.0804 [physics.acc-ph])



6 cell
demonstrator
at Osaka

Beam for Decay Experiments

- Two Options:
 - a conventional stopped muon beam at 1MW based on PSI but a new, dedicated facility for CLFV
 - use same production system as for capture experiments, but flip sign of selected muons
 - will require detailed MCs to choose

Existing Attempts

<https://aip.scitation.org/doi/pdf/10.1063/1.3399332>

- MERIT experiment
 - Liquid mercury — this is an environmental problem (Minamata Convention)
 - Rep rates only about 70 Hz, limited by disruption of the jet. We need x10 faster
- Discussion of muon collider targetry: https://indico.cern.ch/event/1016248/contributions/4282384/attachments/2215324/3752155/MCa_MUC_Targetry_25Mar2021_v1.pdf

Beam Technical Challenges

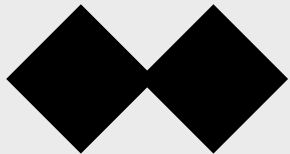
- Things that are very hard that we know how to do:



stopped muon beam at 1MW



compressor ring

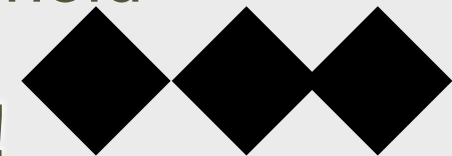


FFA

- Things that are very hard that we don't know how to do

- 1MW target inside a superconducting solenoid

- R&D here closely related to muon collider!



Summary

- Muon-based Charged Lepton Flavor Violation provides powerful searches and constraints for BSM physics
- A new facility at FNAL might provide all three muon channels, $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, and $\mu N \rightarrow eN$ with orders of magnitude more data and open new possibilities in $\mu N \rightarrow eN$ at high Z
 - plus a dark matter experiment and other muon measurements not discussed.
 - technical challenges directly related to muon collider R&D
- We hope for P5 to recommend design of the program with submission to next P5